Charged Cosmic Rays and Photons in AMS

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Abstract: AMS is **a** particle physics experiment in space. During at least 3 year operation on the International Space Station, the AMS-02 detector will provide atmospheric background-free data on fluxes and composition of the Galactic Cosmic Rays with unprecedented precision. The searches for the exotic components of the Cosmic radiation such as primordial antimatter or dark matter signals will also be performed. The new results will allow to improve the knowledge of the Cosmic Ray production, acceleration and propagation mechanisms, and to constrain various models.

Keywords: galactic cosmic rays, antimatter, dark matter, magnetic spectrometer, neutralino.

1. Introduction

Cosmic Rays have been discovered by Victor Hess in 1912 in a balloon experiment. Since then, most of the data, both concerning the composition and the energy spectra came from the balloon-borne experiments, and thus providing measurements which suffer from low statistics and from the contributions of the remaining interactions with Earth atmosphere.

AMS-02 is a large acceptance (0.45 m^2sr active surface) particle detector which when installed on the International Space Station (ISS) will provide data on the fluxes and composition of the Galactic Cosmic Rays (GCRs) in the large range of energy between GeV and TeV with unprecedented precision. Its design ensures the detection of weak signals such as anti-particles and gamma, free from the Earth atmosphere generated backgrounds. This will give for the first time the opportunity to provide outstanding constraints in the study of the most challenging subjects in modern cosmology such as primordial antimatter quest, or dark matter detection in the Galaxy. These measurements need very precise determination of the GCRs fluxes and composition of particles and anti-particles produced in the standard astrophysical processes, via various particle channels (nucleon, nuclei, leptons and gamma). The measurements of the standard astrophysical GCRs by the future AMS-02 mission are the main topic of this paper.

2. The AMS-02 experiment

The Alpha Magnetic Spectrometer (AMS) in its prototype version (AMS-01) was flown for 10 days on board of the Space Shuttle Discovery (1998). This precursor flight provided the most accurate data on the Charged Cosmic Ray (CCRs) fluxes in the MeV/GeV range and the best constraints on the anti-^{4}He/^{4}He ratio, see for review [1]. It has been followed by a detector redesign for a long term mission placed on the ISS.

The AMS-02 detector [2] improves largely the analyzing power and the momentum resolution of charged particles by use of a superconducting magnet and a large double sided silicon tracker, providing a point reconstruction precision of the order of 10 μms and 30 μms in the bending and non-bending plane respectively. AMS-02 is characterized by a low matter budget and a strong redundancy in the particle identification based on the velocity, momentum and charge measurements. The AMS-02 detector is designed to collect huge statistics of the Galactic Cosmic Rays from few hundred MeV/n to few TeV/n, during a minimum period of 3 year mission. Table 1 shows the general performances of the AMS-01 prototype and the future AMS-02 detector. The sub-detector parts of AMS-02 are shown from top to bottom in figure 1:

- Transition Radiation Detector (TRD) composed of 20 layers of straws filled with gas providing electron/hadron separation in the range of 1.5 to 300 GeV, and gamma conversions being detected and measured in the silicon tracker,

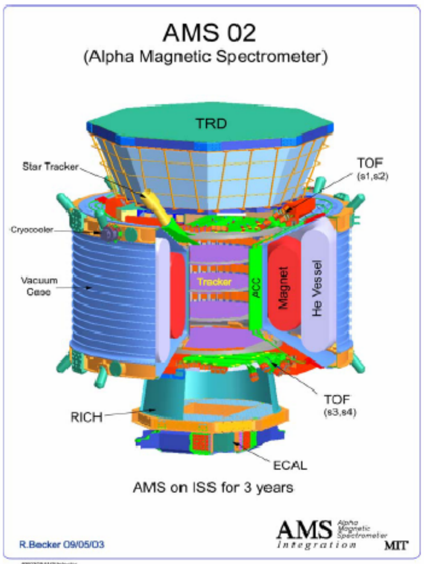

Figure 1: AMS-02 detector to be placed on ISS.

- Time-of-Flight (ToF) with 4 scintillator planes is used for trigger, time, velocity and absolute charge measurements with Δt of ~ 100 psec and $\Delta\beta/\beta$ of few percent,
- Si Tracker (SiTr) embedded in the Superconducting Magnet providing 0.8 T magnetic field, comprises 8 layers of double sided silicon sensors for momentum and signed charge determination with precision on the momentum of 2% at 1 GeV,
- Anti-coincidence Counters (VETO) surrounding the magnet, vetoing particles coming from the sides of the detector,
- Ring Imaging Cherenkov detector (RICH) with pixelized PMTs, for β and absolute charge measurements ($\Delta\beta/\beta \leq 1\%$),
- SPACAL-type Electromagnetic Calorimeter (ECAL) composed of 18 layers of strips of lead and scintillator allowing a 3-D reconstruction of electrons and single gamma showers in the range of 1 GeV to 1 TeV, and energy resolution of ~ 1% at 10 GeV.

This experimental set-up is completed by a pointing device (Star Tracker) and a spatial GPS for the gamma astronomy measurements.

Value	AMS-01	AMS-02
Acceptance	0.15 m^2sr	0.45 m^2sr
Analyzing power (BL^2)	0.15 Tm^2	0.90 Tm^2
Momentum resolution (1 GeV)	10 %	1-2 %
E_{max} (e-)	30 GeV	1.4 TeV
E_{max} (e+)	3 GeV	300 GeV
E_{max} (anti-p)	3 GeV	450 GeV
Statistics	2.9 10^6	10^9
Maximum rigidity	150 GV	1-2 TV

Table 1: general parameters and performances of the AMS-02 detector and of the AMS-01 prototype

To summarize, AMS-02 will determine the fluxes of charged particles with electric charges of 1< Z < 26 in the energy range of 0.1 GeV/n < E < 1 TeV/n. After a 3 year data taking AMS-02 will collect 10^8 H, 10^7 He and 10^5 C candidates with energies above 100 GeV/n. As a benchmark performance value, 10^4 B with energy > 100 GeV are expected to be measured, thus providing a new precise measurement of the boron to carbon ratio, a crucial parameter in all propagation models of the GCRs.

3. Charged Cosmic Rays measurements in AMS-02

The expected performances of AMS-02 detector regarding measurements of the velocity, momentum, signed charge and, by combination of various sub-detector responses, of the particle masses, will allow constraining models for the production, acceleration and propagation of the Galactic Cosmic Rays. Precise measurements of the fluxes of the H and He and of the primary cosmic ray nuclei C, N, O in a wide energy range is related to the injection spectra and can constrain the primary acceleration mechanism. Figure 2 presents proton and helium energy spectra as measured by recent experiments and the AMS-02 reach in this domain.

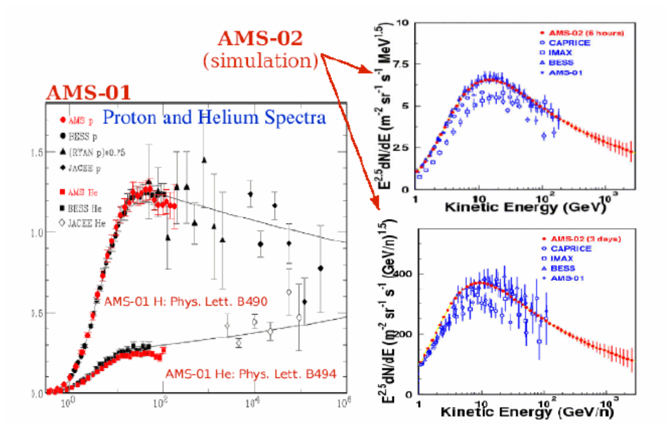

Figure 2: left - proton and right – helium, energy spectra as presently measured and AMS-02 reach.

The fluxes of the secondary particles, absent in the standard astrophysical sources, and their ratios to the primaries producing them in the Inter Stellar Medium, allow to determine the amount of material traversed by CCR since their acceleration, and to constrain parameters of the propagation models. The charge identification in AMS-02 results from a beam test exposure of the Tracker and RICH detectors is shown in figure 3 (left). The B/C ratio in 6 months exposure is also presented in figure 3. One should underline an excellent expected precision of the high energy data.

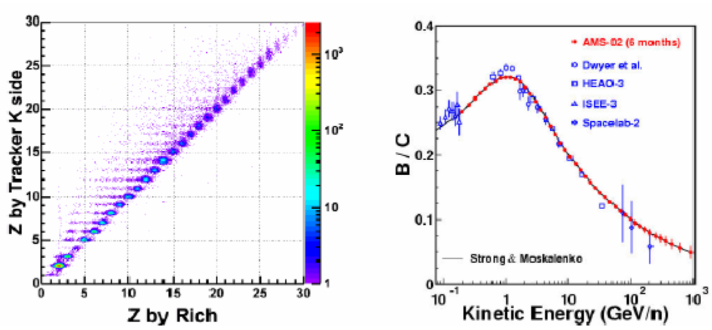

Figure 3: left - charge measurement in AMS-02; right - B/C ratio as measured in 6 months exposure. The B/C ratio simulation follows model in [3].

The anti-proton flux and spectra determination is another important measurement in the field of propagation of the CCRs. The anti-p are produced in the secondary or tertiary interactions of protons and nuclei with ISM. The primary origin of anti-p can only be related to an exotic source such as annihilation of dark matter WIMPS. Various theoretical studies have shown that the present data does not suggest any contribution of an exotic component. Figure 4 shows the present measurements of anti-p/p ratio and energy spectra as measured in future by AMS-02.

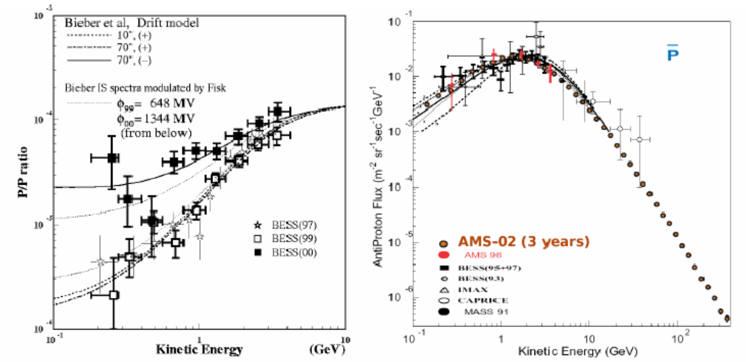

Figure 4: recent measurements of anti-p/p ratio and energy spectra as measured in future by AMS-02.

As regards the stable light isotope measurements, AMS-02 will be able to identify deuterium from hydrogen and ^{3}He from ^{4}He in the energy range of 1 < E < 10 GeV/n. After 3 years of data taking, AMS-02 will identify ~10^{8} D and ^{3}He nuclei. Figure 5 shows deuteron/proton (left) and ^{3}He/^{4}He (centre) ratios. Finally, the ratio of unstable to stable isotopes can be used for an estimation of the cosmic ray confinement time in the Galaxy and, in the diffusion models [4], the effective thickness of the galactic halo. AMS-02 will be able to identify ^{10}Be from the stable ^{9}Be in the energy range of 0.15 < E < 10 GeV/n. After 3 years of data taking, AMS-02 will identify ~10^{5} ^{10}Be in this energy range. The expected sensitivity after 1 year is shown in figure 5 (right).

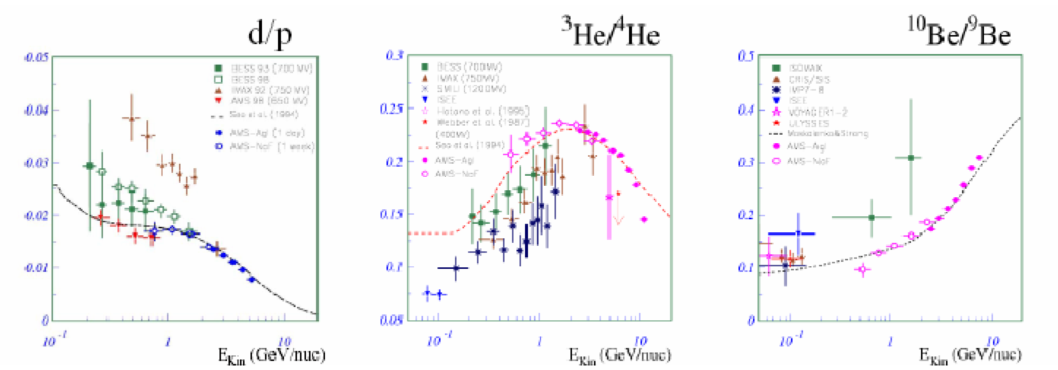

Figure 5: various isotopic ratio from present data and predictions for AMS-02, d/p (1 week/1day), ^{3}He/^{4}He (1day), ^{10}Be/^{9}Be (1 year).

Energetic electrons or positrons cannot diffuse more than few kpc. They are sensitive probes of the Local Bubble [5] and its neighbourhood. The positron/electron ratio measurement may also provide an interesting probe of exotic processes. The present status of measurements is shown in figure 6 where the electron spectra (left) and e^{+}/e^{-} ratio (right) are displayed. One may notice lack of agreement between results from different experiments and need of understanding of the systematic effects concerning the normalisation of the spectra. The role of the future precision AMS-02 data in this domain will be decisive.

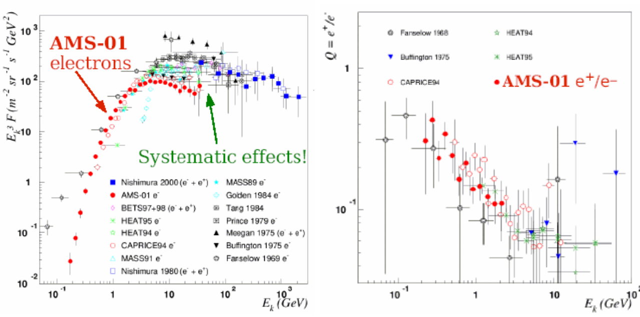

Figure 6: electron energy spectra (leftt) and e^{+}/e^{-} ratio (right) from present data

4. Exotic searches in AMS-02

During Big Bang era, the matter and antimatter were equally distributed in the Universe. The present observation data indicates a strong dominance of the matter in our cluster of galaxies, so a baryogenesis mechanism was proposed by various theories [6]. These theories would require strong CP and C violation processes not observed yet. However, the search for the primordial antimatter, anti-He and anti-C can be considered as an outstanding goal in the modern cosmology. AMS-02 will improve the present best limits on the anti-He/He ratio by a factor of 10^3. Figure 7 shows the latest results and AMS-02 reach for the anti-He/He ratio (left) and anti-D flux (right) measurements.

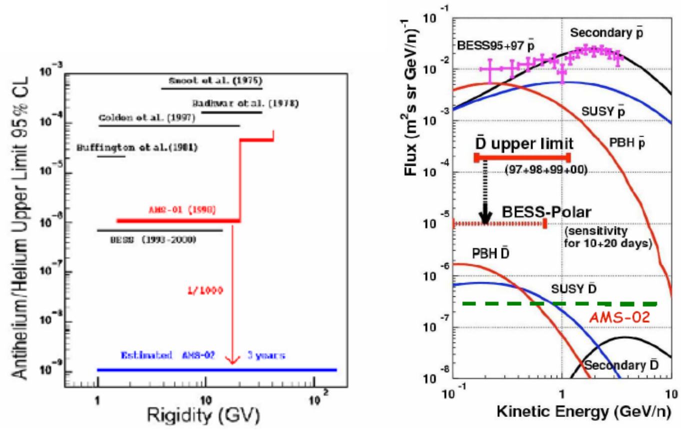

Figure 7: left - anti-He/He ratio as a function of the rigidity as provided by several experiments and the AMS-02 expected limit after a 3-year exposure; right – limits on anti-D fluxes.

As stated previously, the electron and positron measurement may lead to the dark matter detection in the vicinity of the solar system. In particular, the $e^+/(e^+{+}e^-)$ ratio can be considered as a very sensitive probe of the annihilation channel of WIMPs. Various supersymmetric models [7] as well those proposed by the extra dimension Kaluza-Klein theories [8], predict large branching ratios in the leptonic channels. The observed bump in the positron ratio by HEAT experiment [9] at around 7 GeV was recently confirmed by the latest re-analysis of the AMS-01 data, see figure 8 (left) [10]. This enhancement, difficult to be described by standard astrophysical processes, may find its explanation in the frame of the supersymmetry as shown in figure 8 (right) for a given model [11].

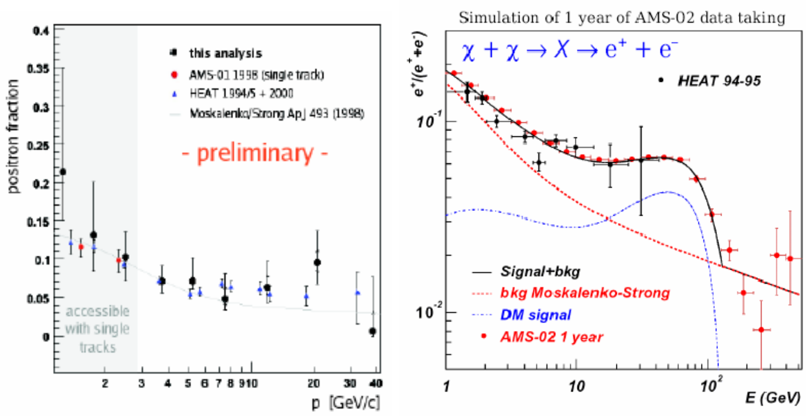

Figure 8: left - e+/e- ratio as a function of momentum from HEAT experiment and latest AMS-01 analysis, right - predictions for AMS-02 in a frame of a MSSM model

AMS-02 will detect high energy gamma rays up to few hundred GeV by reconstruction of e^+e^- pairs in the Tracker and of single photons in the ECAL. The pointing precision on the astrophysical sources of the order of 0.1-0.2° obtained with Star Tracker and Tracker measurements will allow the detection of the most brilliant galactic and extra-galactic sources such as Gamma Ray Bursts, Pulsars or Active Galactic Nuclei, as discussed elsewhere. The AMS potential for the dark matter detection from the Galactic Centre has been studied in ref. The AMS-02 sensitivity to the integrated fluxes above 3 GeV originating from a dark matter source is confronted to those expected in the mSUGRA, AMSB and Kaluza-Klein models [12] as a function of particle masses. In fig. 8, the mSUGRA scan, AMSB and Kaluza-Klein results are shown for a standard Navarro-Frenk-White (NFW) [13] dark matter density profile and 3 year exposure time. The 95% CL was obtained by a 3σ fluctuation of the diffuse gamma emission as measured by EGRET ranges below 10^{-9} gamma per $cm^{-2}s^{-1}$. and will allow to exclude/discover several exotic models.

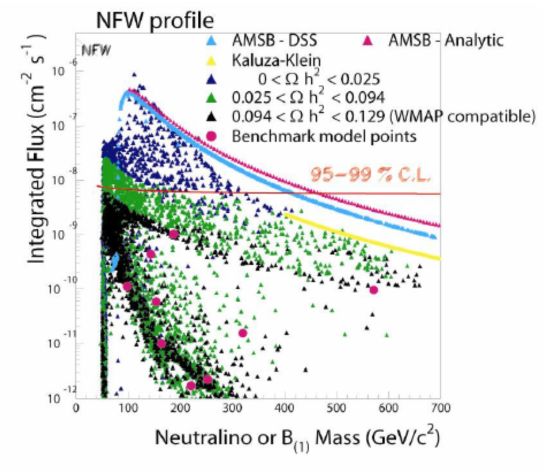

Figure 5: the integrated γ flux for energies above 3 GeV in a 3 year exposure time from the Galactic Centre, as a function of the neutralino or Kaluza-Klein mass, assuming a NFW dark matter profile.

Summary

The particle physics detector (AMS-02) placed on the ISS will provide results on the GCR fluxes and composition, and in the cosmological search sectors such as primordial anti-mater and dark matter quests. The identification capabilities of the detector, in a wide energy range and a large data sample collected during 3-year exposure will allow to constrain the current models of the production, acceleration and propagation of the GCRs. The precise measurement of the standard astrophysical sources of the GCRs is required in case of the future discoveries in the New Physics domains.

References

[1] M. Aguilar, et al., Phys. Rep. Vol.366, no 6 (2002) 331.
[2] J. Alcaraz, et al., NIM A478 (2002) 10; AMS Collaboration: AMS on ISS. *Construction of a particle physics detector on the ISS,* to be published Nucl. Instr. Methods A.
[3] A.W. Strong and I. Moskalenko, ApJ 509 (1998) 212.
[4] D. Maurin et al., A&A 394 (2002) 1039
[5] J. Maiz-Apellaniz, ApJ 560 (2001) L83.
[6] A. Cohen, A. de Rujula and S. Glashow, ApJ 495 (1998) 539.
[7] G. Jungman and M. Kamionkowski, Physics Reports 267 (1996) 195.; E.A Baltz, J. Edsjo, K. Freeze and P. Gondolo, Phys. Rev. D 65 (2002); L. Bergstrom, J. Edsjo and P. Ullio, Astrop. Journal 526 (1999) 215.
[8] G. Bertone, G. Servant and G. Sigl, Phys. Rev. D 68 (2003) 044008.
[9] S. W. Barwick,, et al. Phys. Rev. Lett. 75 (1995) 390.
[10] J. Olsem, UCLA DMS conference, (2006).
[11] P. Maestro, PhD Thesis,University of Sienna, AMS-Note 2003-01-01.
[12] A. Jacholkowska, G. Lamanna, E. Nuss, et al, astro-ph/0508349, Phys.Rev. D (2006).
[13] J.F. Navarro, C.S. Frenk and S.D.M. White, ApJ 490 (1997) 493.